Nishina School/Lecture 6
仁科学校/第六講義

Scintillator (闪烁器)

Oct. 4, 2012, 11:00~12:00

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Contents of Today's Lecture

1. Introduction
2. Interaction of radiation with matter
   - 2-1) Energy loss of charged particles in matter
   - 2-2) Interaction of photons with matter
3. Scintillation Counters
   - 3-1) Basic of Scintillator
   - 3-2) How to convert light to signal
   - 3-3) Response of Scintillators

   (3-1 to 3-3: Main topic of this lecture)
4. Applications
5. Review

0. Text Books

Two very good text books for learning radiation measurement and detectors

1. Glenn F. Knoll,

   "Radiation Detection and Measurement",

   John Wiley & Sons, Inc., New York

   (4th edition, 2010)

2. W. R. Leo,

   "Techniques for Nuclear and Particle Physics Experiments", Springer-Verlag

   (2nd edition, 1994)

1-1. What is scintillation?

Scintillation (火花的迸出):

A flash of light produced in a phosphor by absorption of an ionizing particle or photon.

(ref: The American Heritage Dictionary)

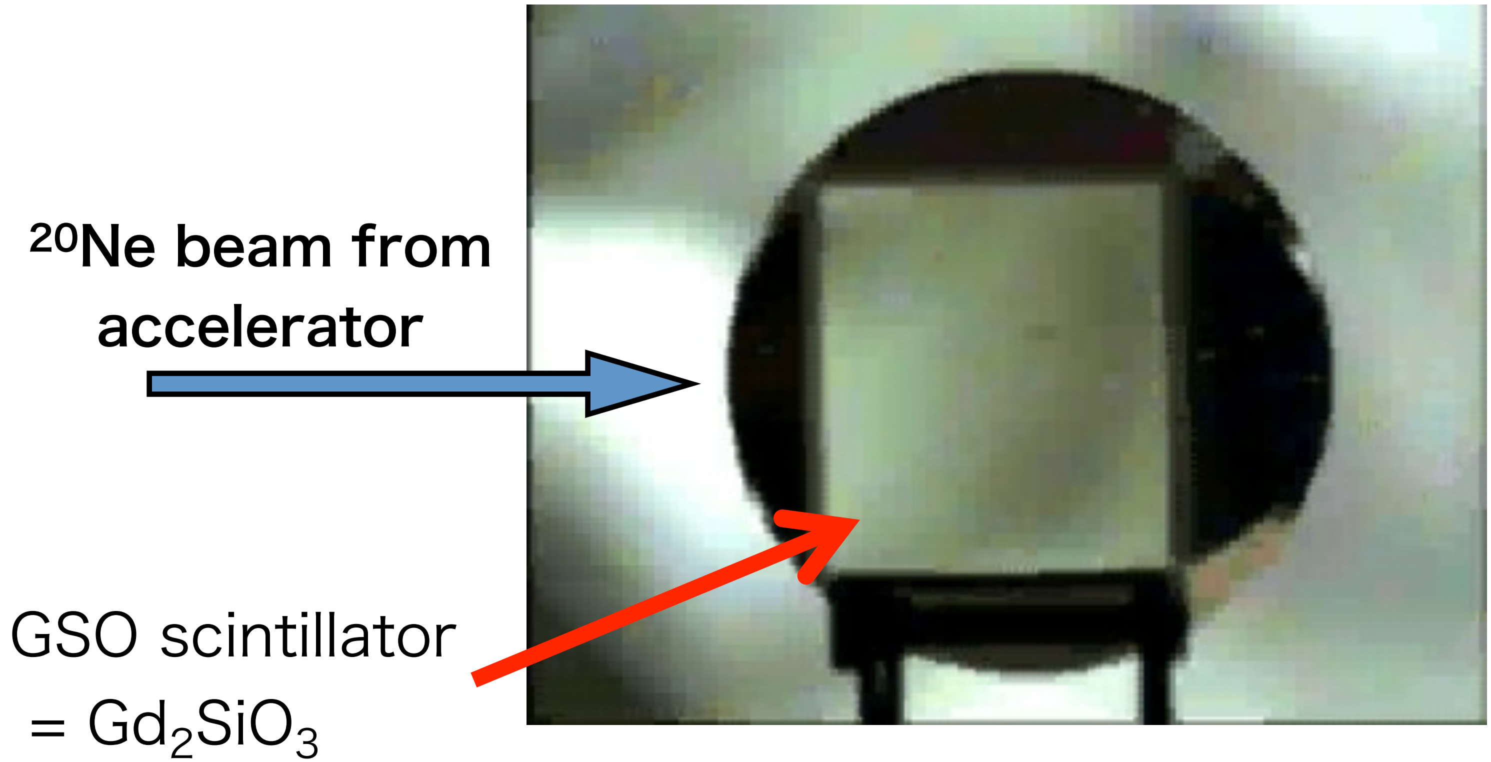
Scintillation is a good method to visualize radiation.

- How is the light produced?
- How to detect the light?
- What kind of phosphor can we use?
- What is the application of scintillation?

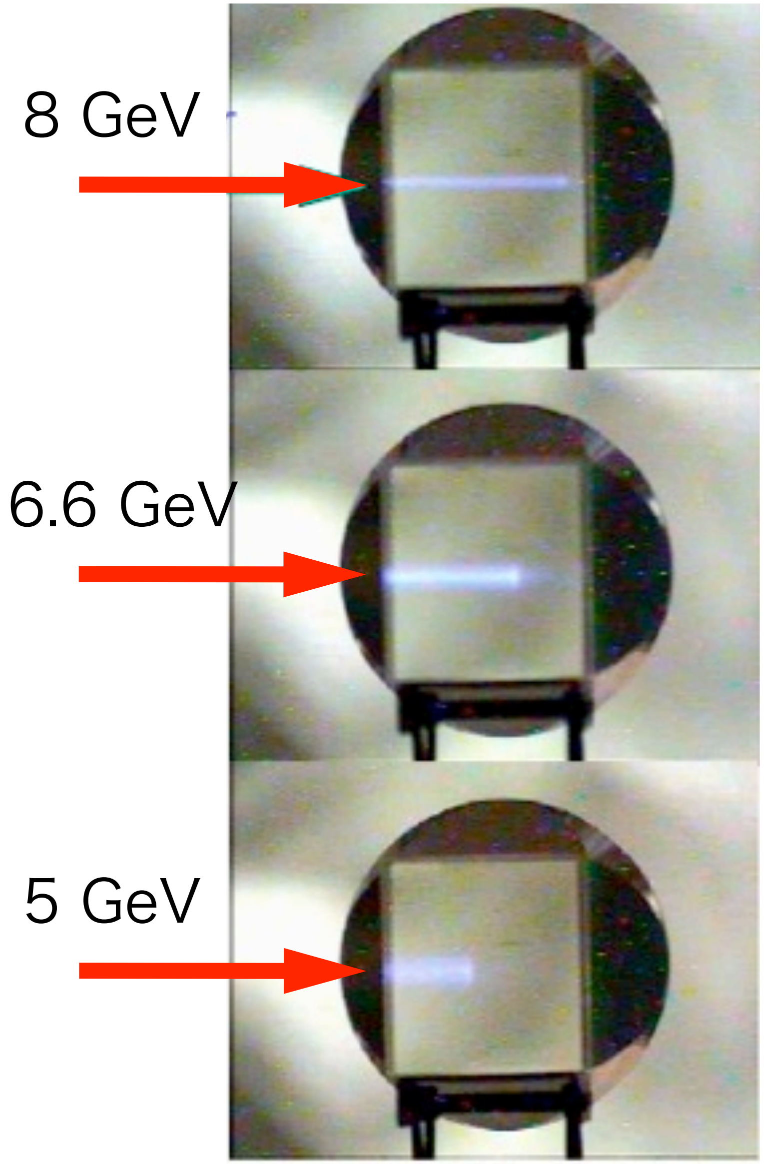
➔ Those are the topics of this lecture!

1-2. Scintillation Light (1/2)

- An example of scintillation light
- ^{20}Ne beam injection from a heavy-ion synchrotron



1-2. Scintillation Light (2/2)



- Passage of <u>charged particles</u> triggers scintillation light.
- The lower-energy beam seems to stop in the middle of scintillator.
- The beam is slowing down inside the scintillator. A whole kinetic energy of beam is deposited inside the scintillator.
- Kinetic energy should be converted into the scintillation light···

Why & How?

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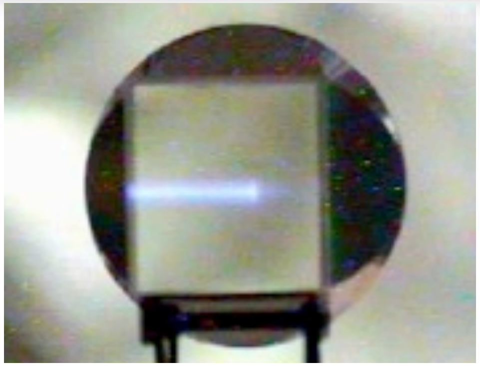
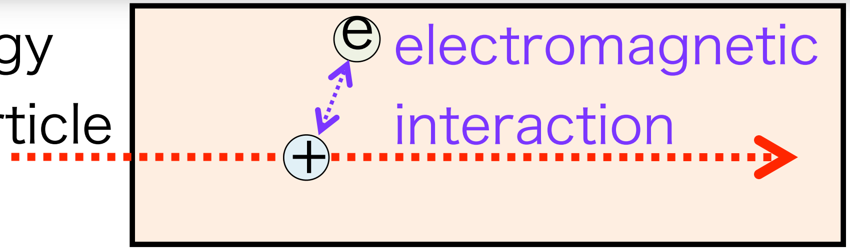
2-1. Energy Loss of Charged Particles in Matter



What is happening
in the matter?

A high-energy
charged particle



EM interaction causes;

1. Ionization of atoms
2. Excitation of atoms / molecules

◆The Bethe-Bloch formula (energy-loss formula)

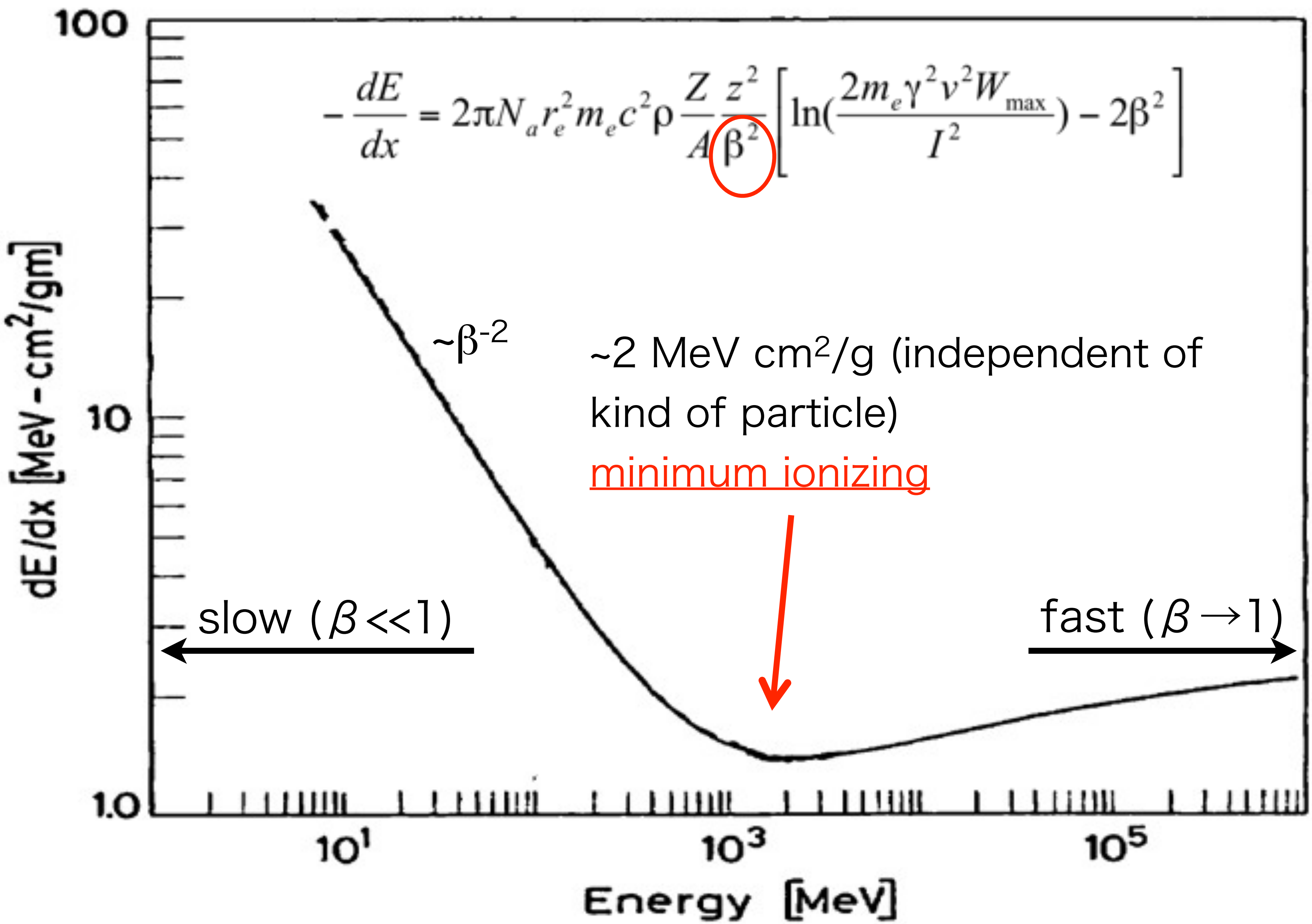
$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2\right]$$

N_a: Avogadro's number
r_e: classical electron radius
m_e: electron mass
c: speed of light
ρ: density of absorbing material
Z: atomic number of absorbing material
A: atomic weight of absorbing material

β: velocity of incident particle (v/c)
γ: Lorentz factor of incident particle [$1/\mathrm{sqrt}(1-\beta^2)$]
z: charge of incident particle
W_{max}: maximum energy transfer in a single collision
I: mean excitation potential

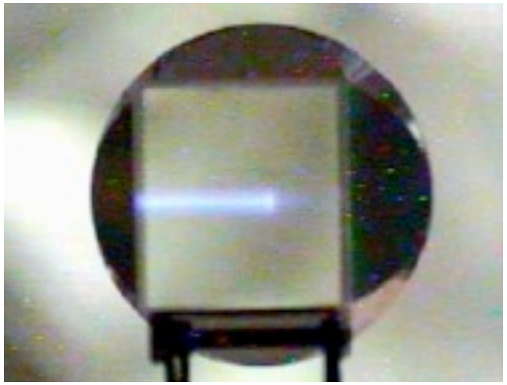
Independent of mass of incident particle

2-1. Energy Loss of Charged Particles in Matter

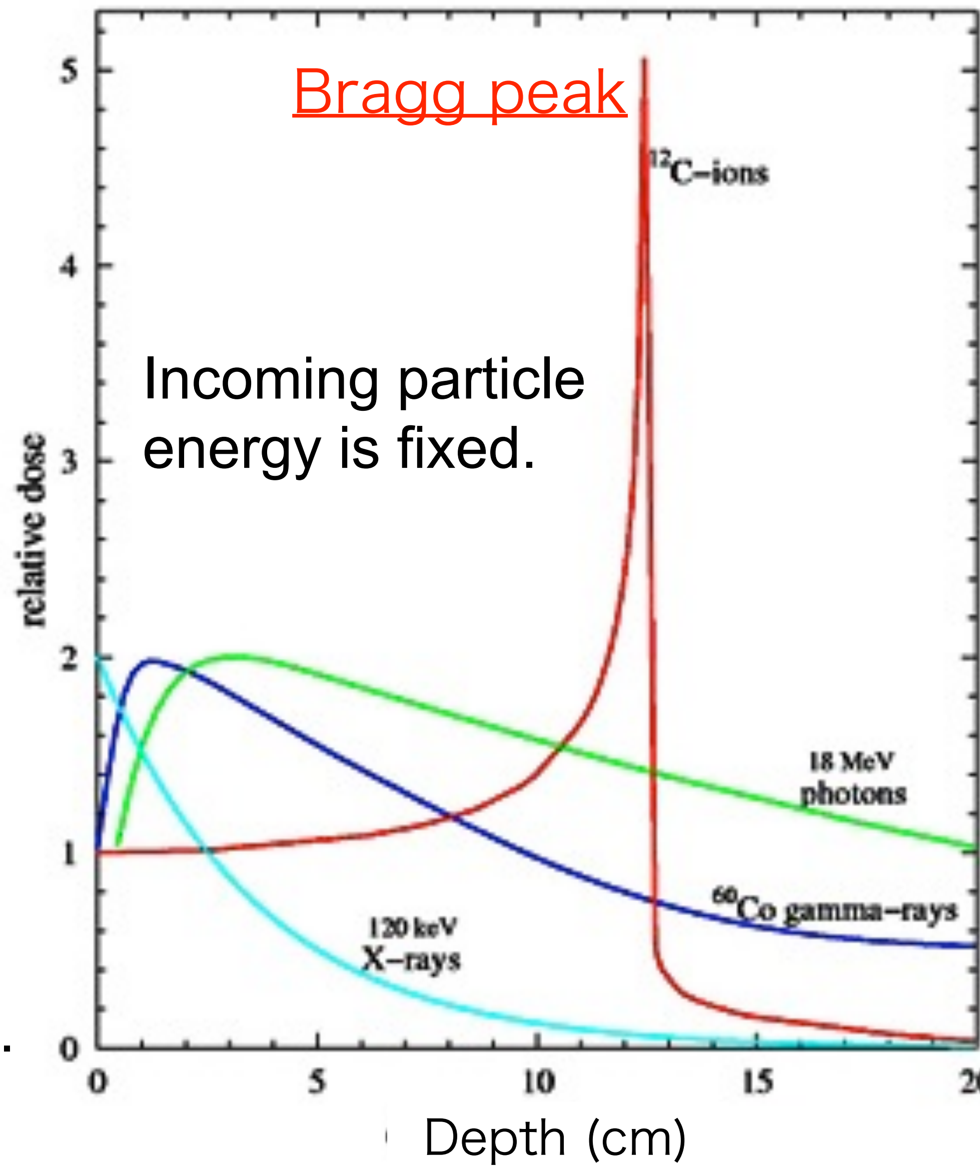


2-1. Energy Loss of Charged Particles in Matter

Ref: GSI web



Q: How much energy deposit per unit length?



Bragg peaks are used for (heavy) ion radiotherapy to burn the tumors of cancers.

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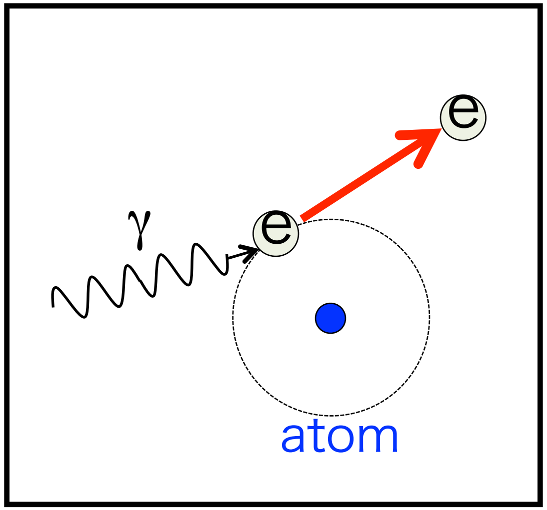
2-2. Interaction of γ-ray with Matter

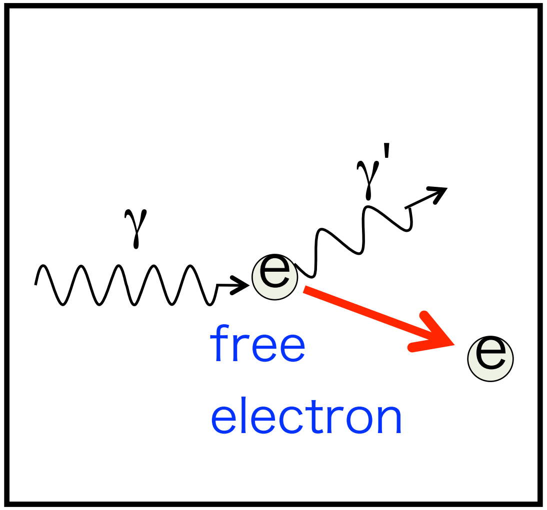
◆ Three Interaction Processes (produce e^-.)

(1) Photoelectric effect



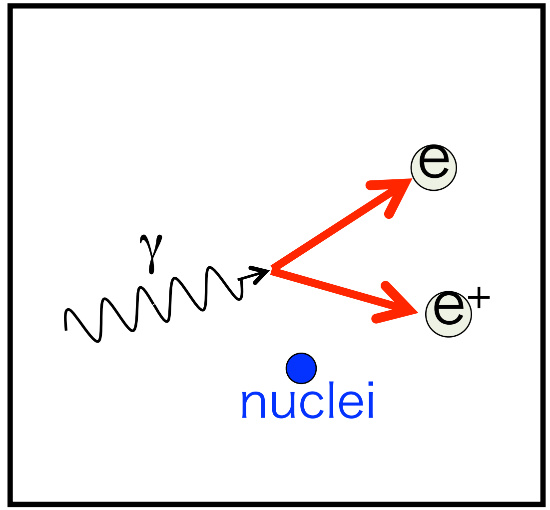
- Gamma-ray knocks-on the electron bounded in an atom and is absorbed.
- $\sigma \propto Z^{4\text{-}5} \times E^{-3.5}$
- High-Z material better.

(2) Compton scattering



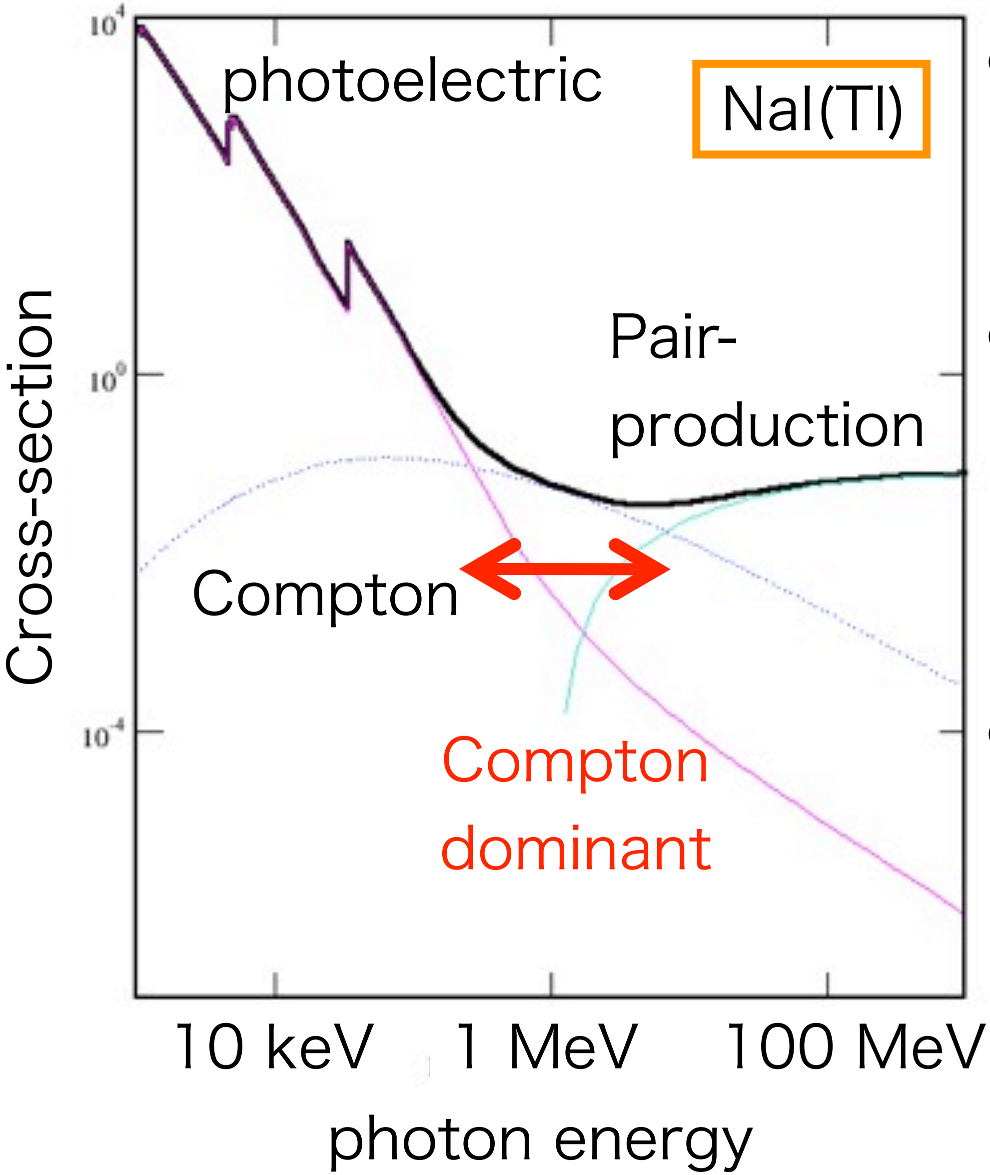
- γ-ray knocks-on a free electron and is scattered.
- Klein-Nishina formula
- $\sigma \propto Z$: # of electrons

(3) Pair-production



- Only occurs in strong E field near nuclei.
- $E_\gamma > 2m_e = 1.02$ MeV/c^2
- Important for MeV γ-ray

2-2 Reaction cross-section of photons with matter



- Regime of three reactions
  Photoelectric < Compton < pair-production
- Compton scattering is the most dominant process around 1 MeV. Most of nuclear γ-rays have energy around 1 MeV.
- We cannot easily determine total energy loss via Compton scattering because of the escape of scattered photon.

→ MeV γ-ray universe is still mystery.

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Main topic of this lecture

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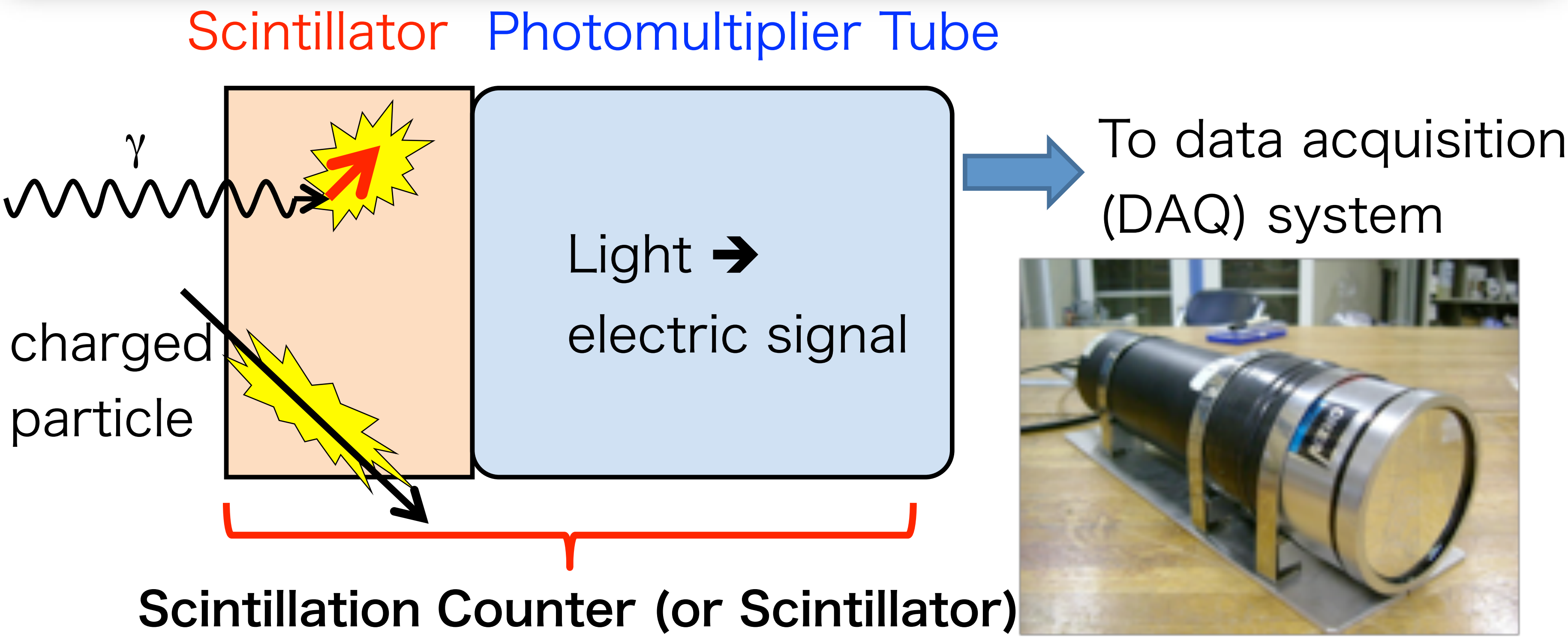
3. Scintillation Counter



1. Passage of charged particles excite molecule or crystal
2. Scintillation light is emitted
3. The light is collected and converted into a signal with PMT
4. The electric signal is recorded with a data acquisition system

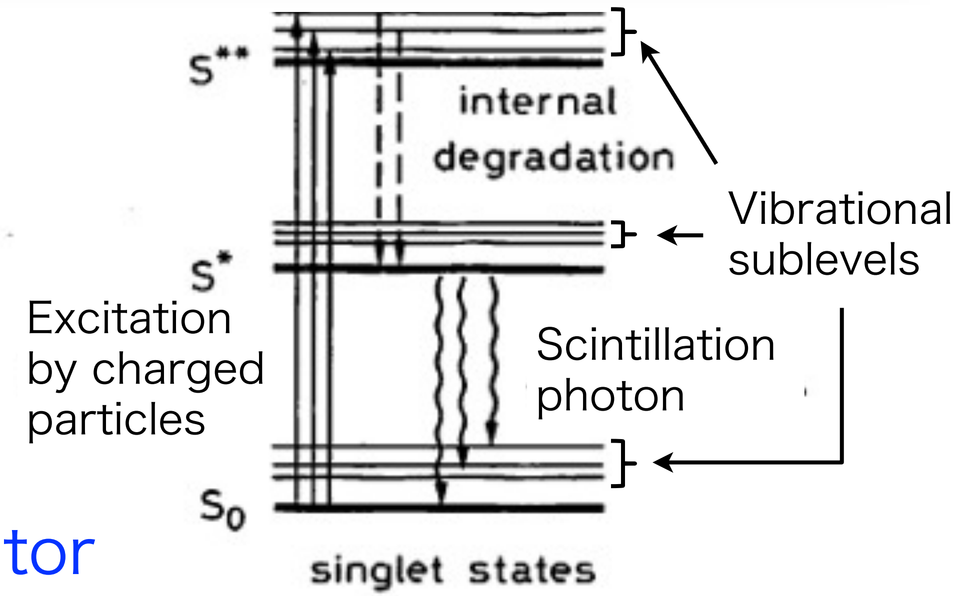
3-1. Scintillator

- A lot of materials can be a candidate of scintillation counters!
  - Good light yield and less self-absorption
  - Fast pulse of light
  - Good linearity (Energy vs. output pulse height)
- Two classes of scintillators
  - Organic Scintillators : Plastic and liquid)
  - Inorganic Crystal Scintillators: NaI(Tl), CsI(Tl), BGO, GSO

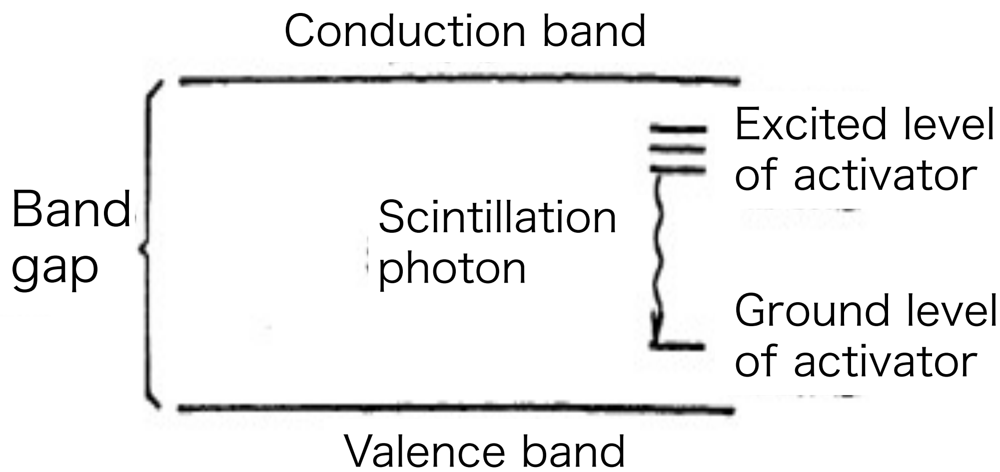
	Organic Scintillator	Inorganic Scintillator
Stopping power	Low (due to low-Z)	High (due to high-Z)
Time response	Fast (~ns)	Slow (0.1~1us)
Light yield	Small	Large
Usage	Timing measurements	Gamma-ray spectroscopy
NOTE	Easy to shape	Some crystals are hygroscopic

3-1. Fluorescence mechanism

- **Organic Scintillator**
  - π-electronic structure of molecule
  - Fast response
  - Low light yield



- **Inorganic Crystal Scintillator**
  - Band-structure of crystal
  - Slow response
  - High light yield
  - Activator (e.g. Tl in NaI) needed to suppress self-absorption

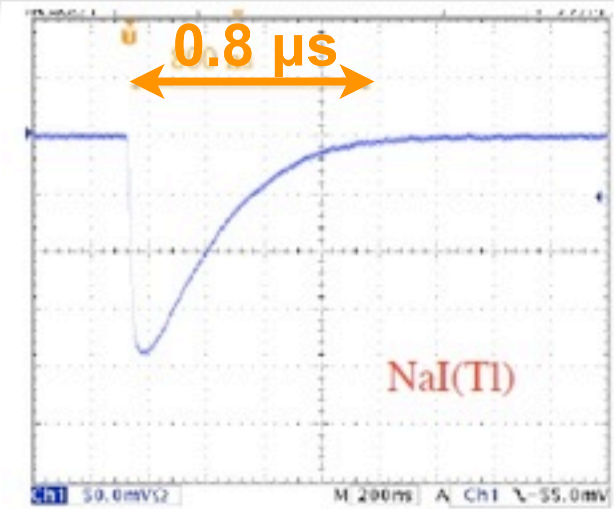


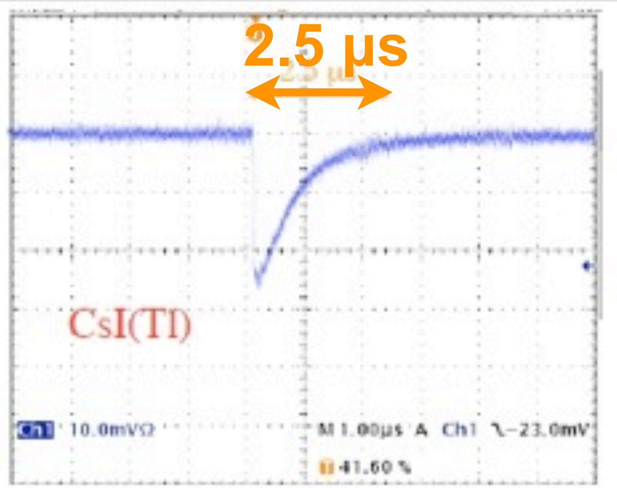
3-1. Inorganic Crystals

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	6.71
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.12	1.14	1.37
Interaction Length (cm)	41.4	37.0	37.0	29.9	21.8	21	22
Refractive Index	1.85	1.79	1.95	1.50	2.15	1.82	1.85
Higroscopy	Yes	Slight	Slight	No	No	No	No
Luminescence (nm)	410	560	420 310	300 220	480	420	440
Decay Time (ns)	230	1300	35 6	630 0.9	300	40	60
Light Yield (%)	100	45	5.6 2.3	21 2.7	9	75	30

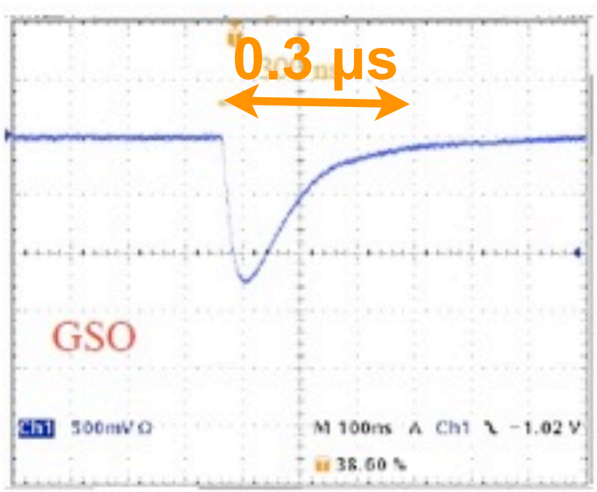
Energy Loss (eV/photon) 25 300

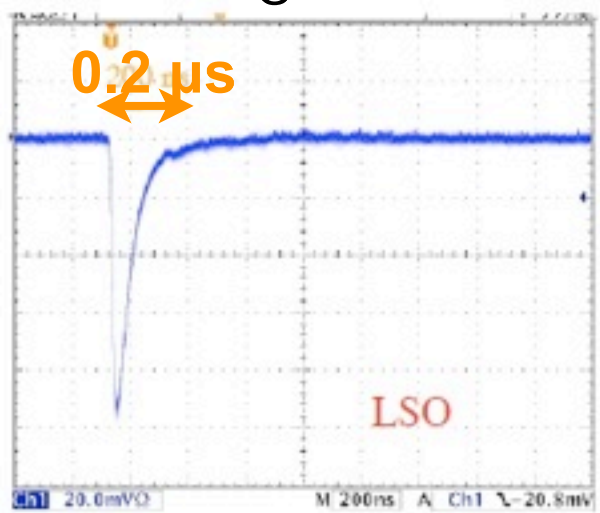
3-1. Signals from inorganic scintillators





Different decay time among different inorganic scintillators.

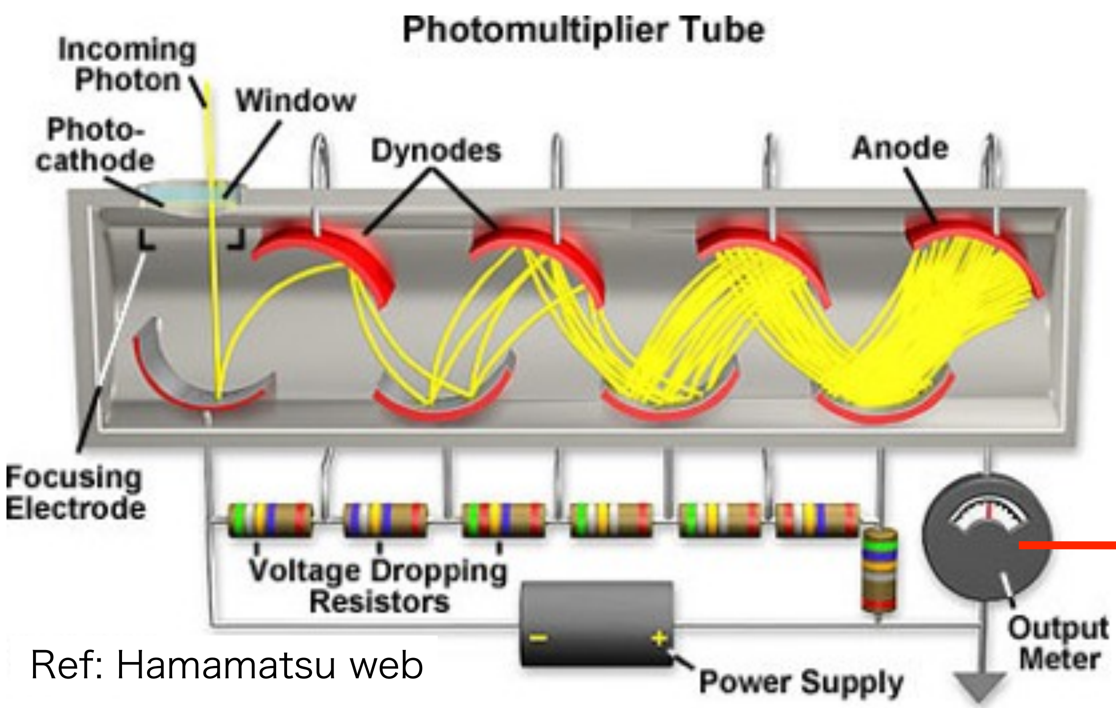




How to convert the scintillation light into electric signals?

3-2. Photomultiplier Tubes (PMTs)

- Noble light detector!
- One optical photon can be detectable.
- Gain ~ $10^{5\text{-}6}$ (electric amplification factor)
- Efficiency ~ 25% (photocathode)



Ref: Hamamatsu web

Photocathode: convert a photon into a photoelectron via photoelectric effect

Dynode: coated by alkali metal. Multiply electrons.

Anode: the last stage of the multiplication process.

→ current

3-2. Photodiodes

- A semiconductor photon detector

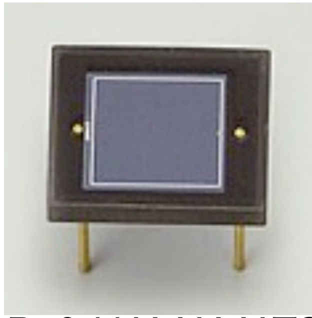
Scinti.

PMT

Small size
Low cost
Low power

Scinti.

Photo diodes



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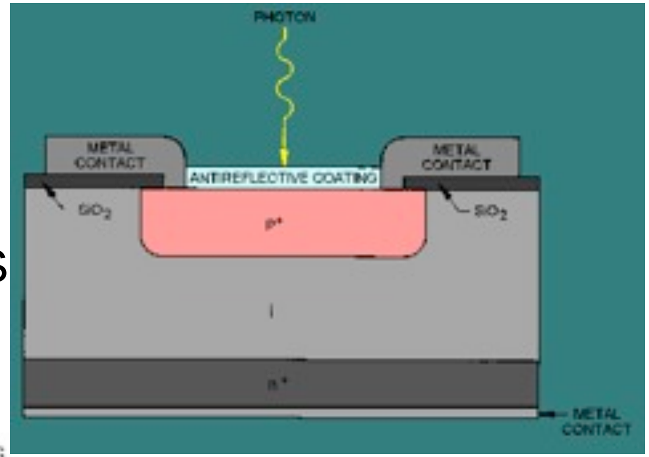
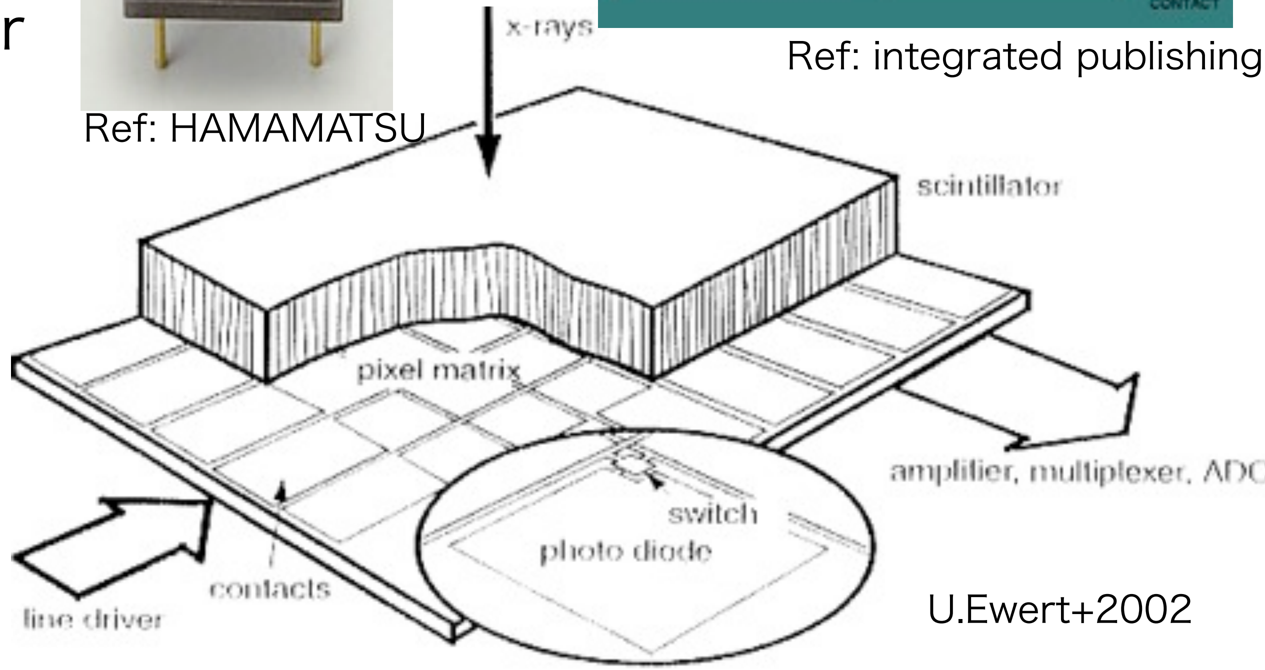


Ref: integrated publishing

Imaging scintillation counter with an advanced CMOS photodiode



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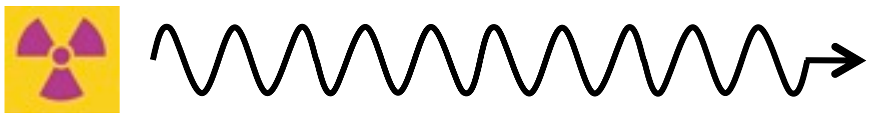
3-3. Detector Response

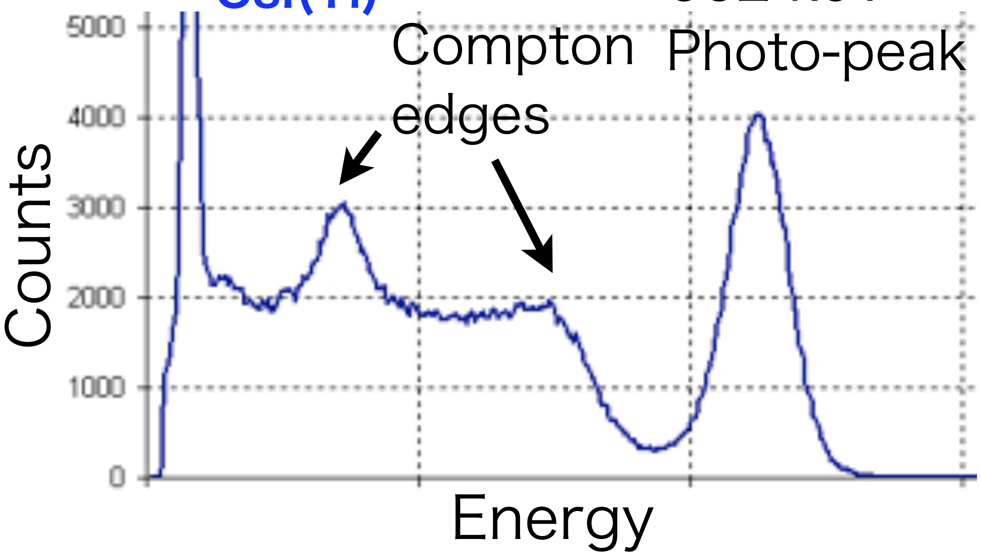
What kind of spectrum do we have when a scintillation detector is irradiated with monochromatic γ-rays?

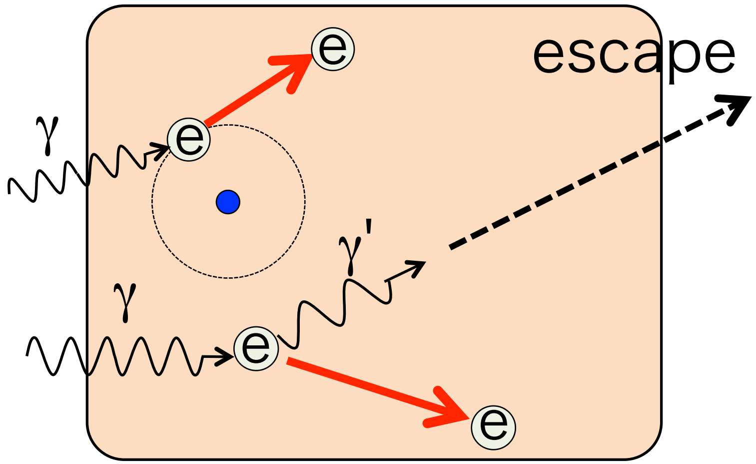
662 keV γ-ray



^{137}Cs

CsI(Tl) + PMT



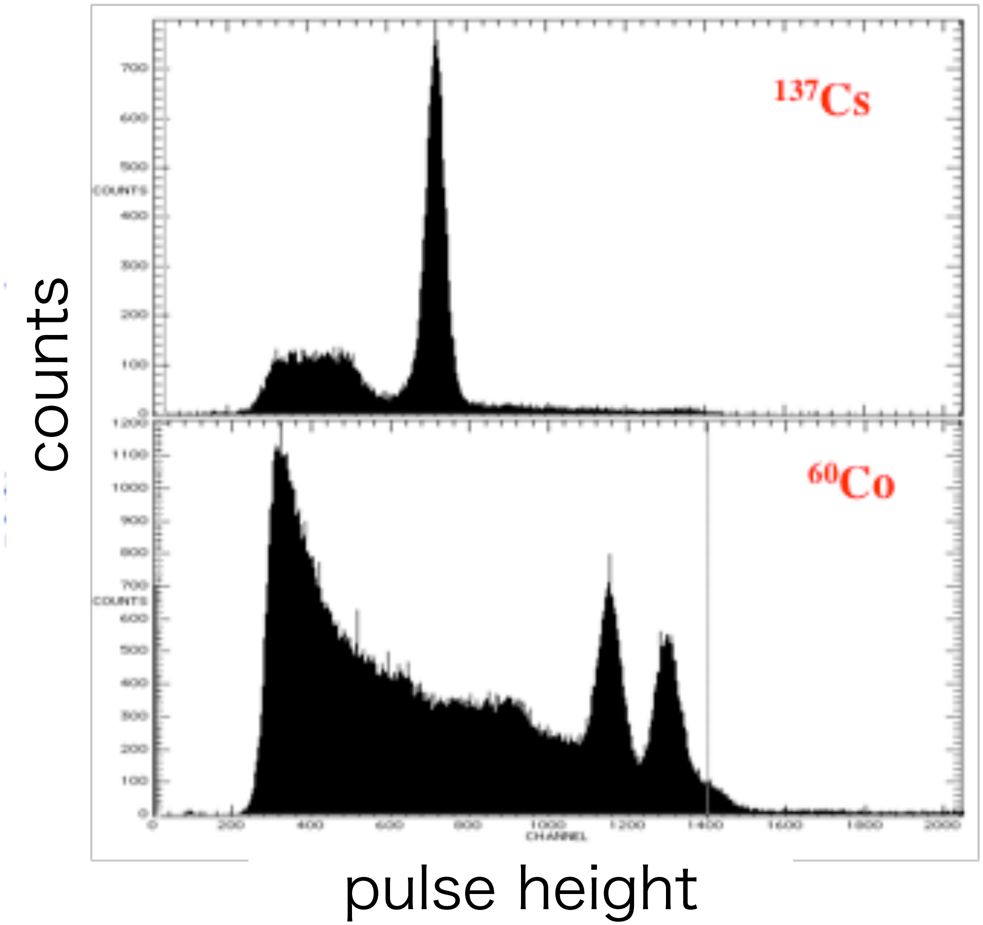


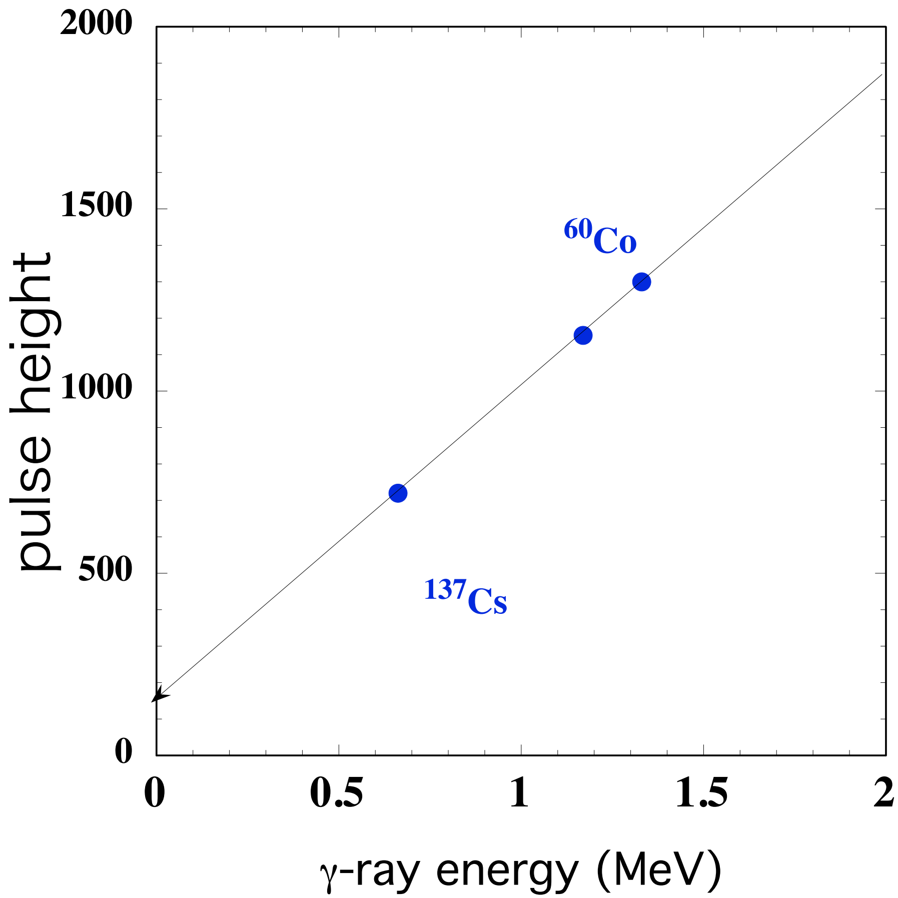
Detector response

3-3. Linearity

- Pulse height is proportional to the γ-ray energy
  - ex. radiation sources such as
    - ^{137}Cs : 0.662 MeV
    - ^{60}Co : 1.17, 1.33 MeV

For spectroscopy, linearity is very important.





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Main topic of this lecture

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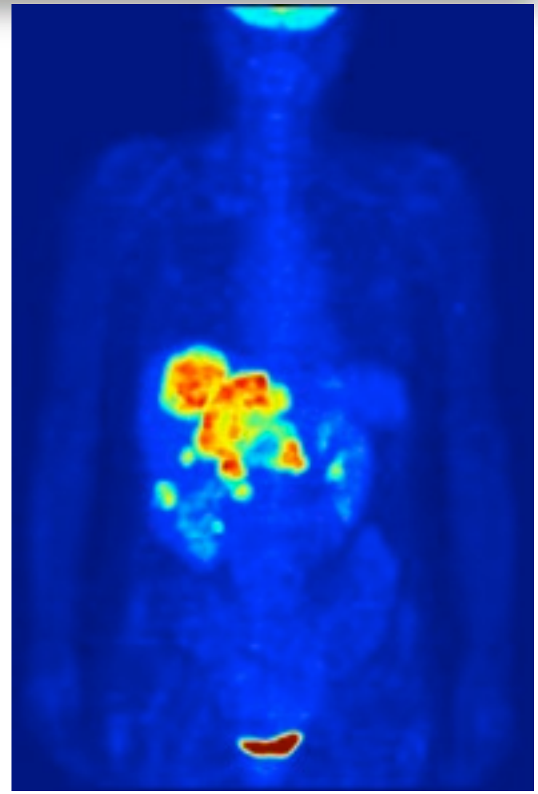
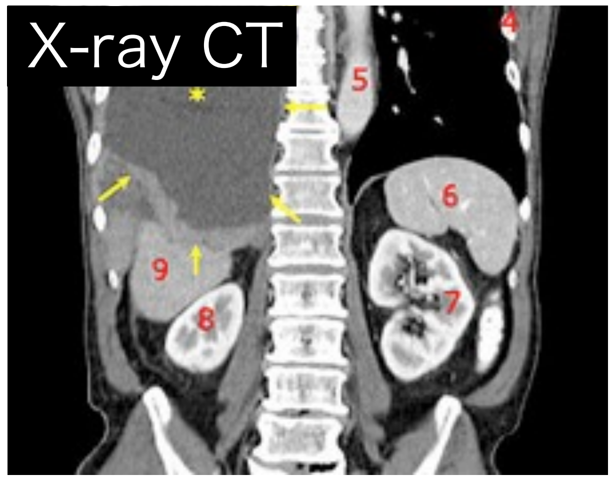
4-2. Positron Emission Tomography (PET)

X-ray CT: can see shape of organs

PET: can see a cancer itself

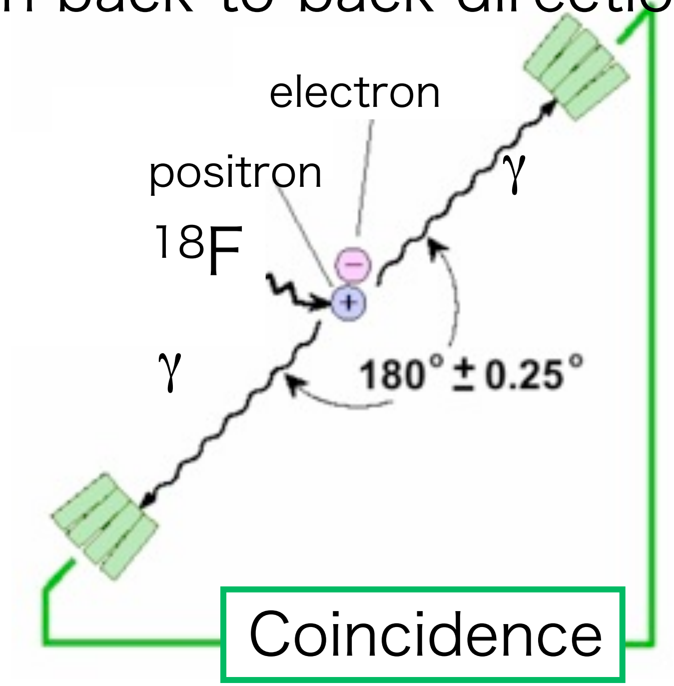


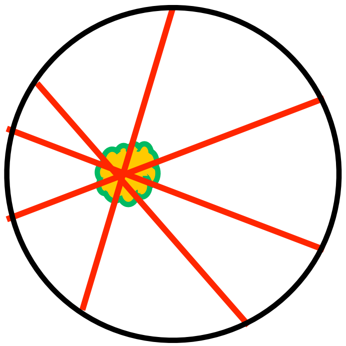
- Concept is quite simple
    1. Cancer consumes much glucose than normal cell.
    2. Labels glucose with appropriate gamma-ray emitter.
    3. Injects the labeled glucose into body and it should be accumulated at the cell of cancer.
    4. Detect gamma-ray and trace back the glucose accumulated point.
- How to measure the direction of a gamma-ray?

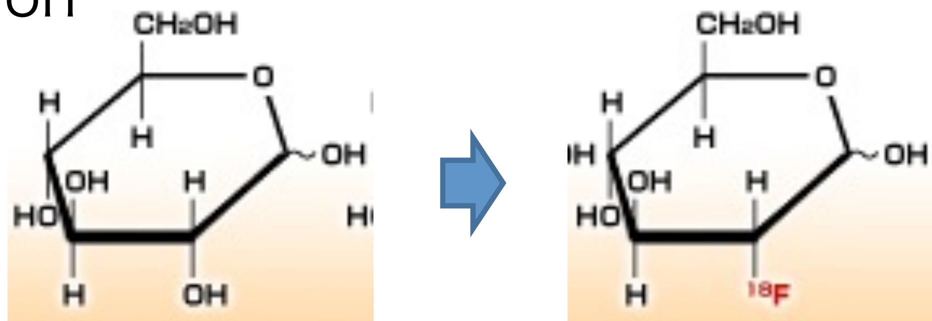


4-2. Positron Emission Tomography (PET)

positron-electron annihilation emits two gamma-rays in back-to-back direction.



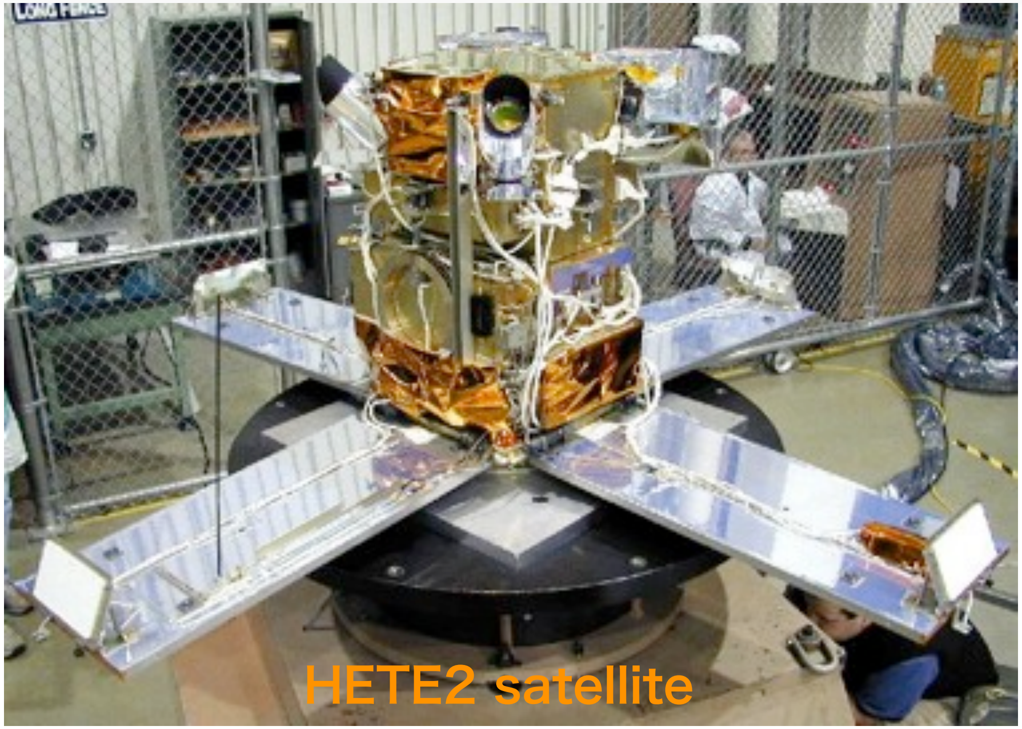


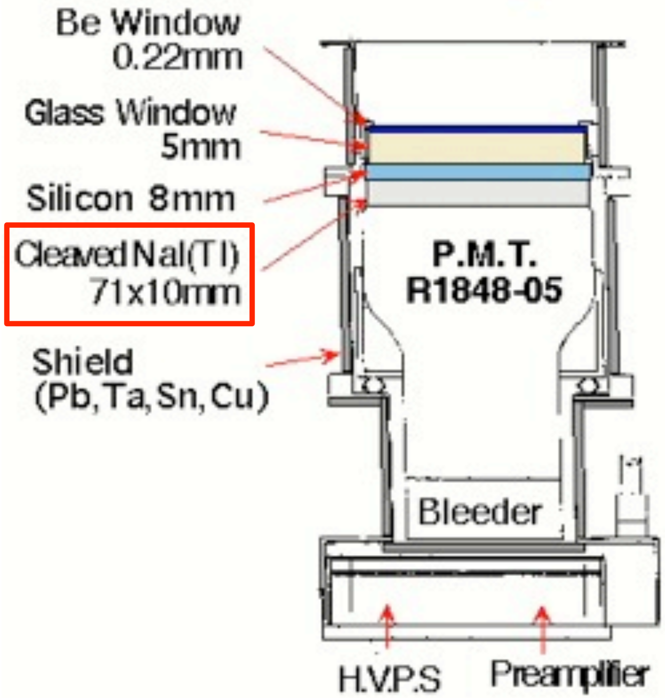


glucose fluoro-deoxy-glucose

^{18}F β^+ decays (t ~1.8 hr)

4-3. Scintillators In Space (HETE2)





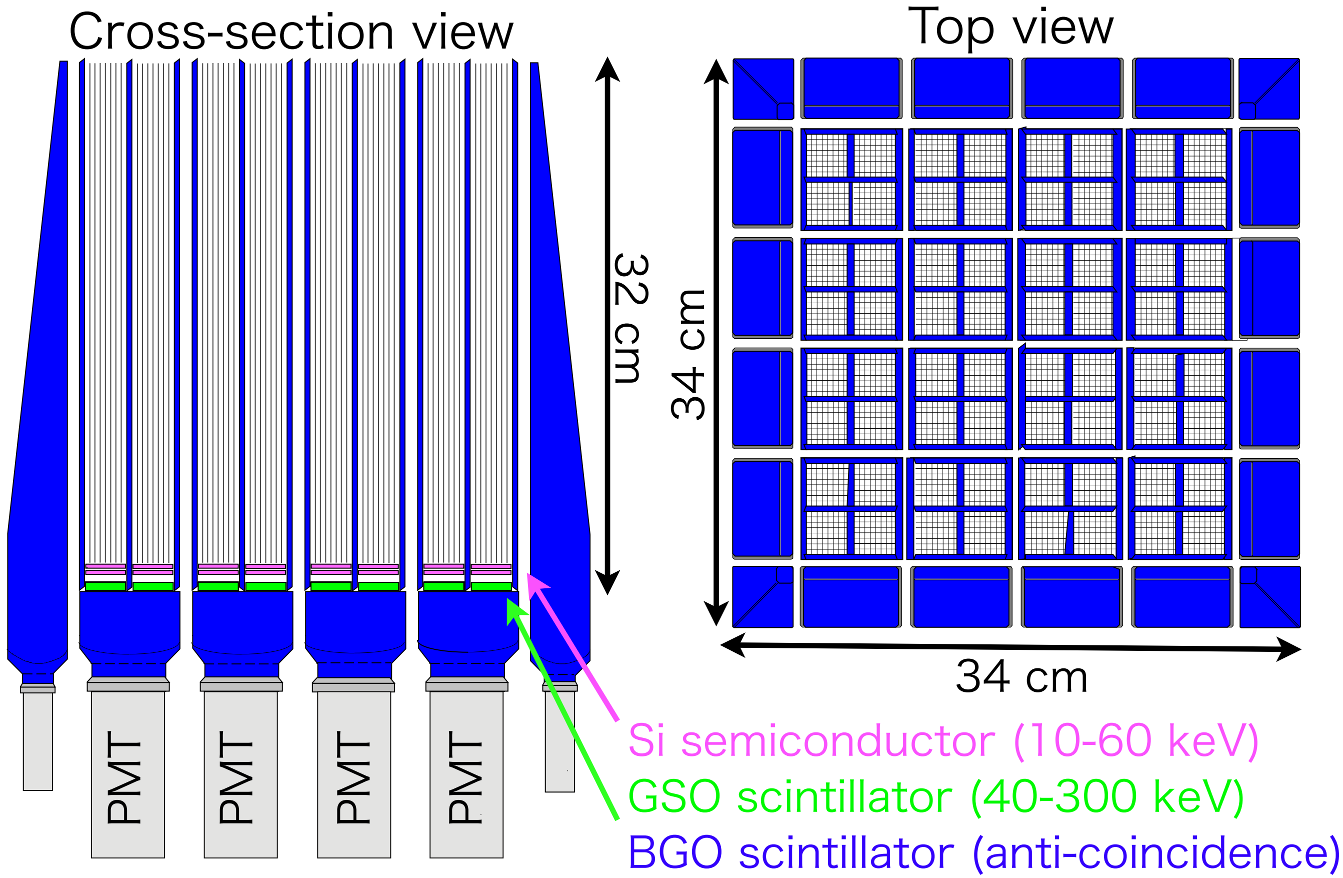
- HETE2 had detected γ-rays which traveled for >100 million years from the supernova explosion of very heavy stars occurred in the early universe. (γ-ray burst)

Scintillators are typical γ-ray detectors
in high energy astrophysics

4-3. Scintillators In Space (Suzaku)

- Cosmic X/γ-rays are very faint, while background signals induced by cosmic radiation are very high. Background reduction is essential to develop high-sensitive detectors.

Hard X-ray detector onboard Suzaku (朱雀)



Scintillation counters are used as X/γ-ray detectors as well as anti-coincidence shields

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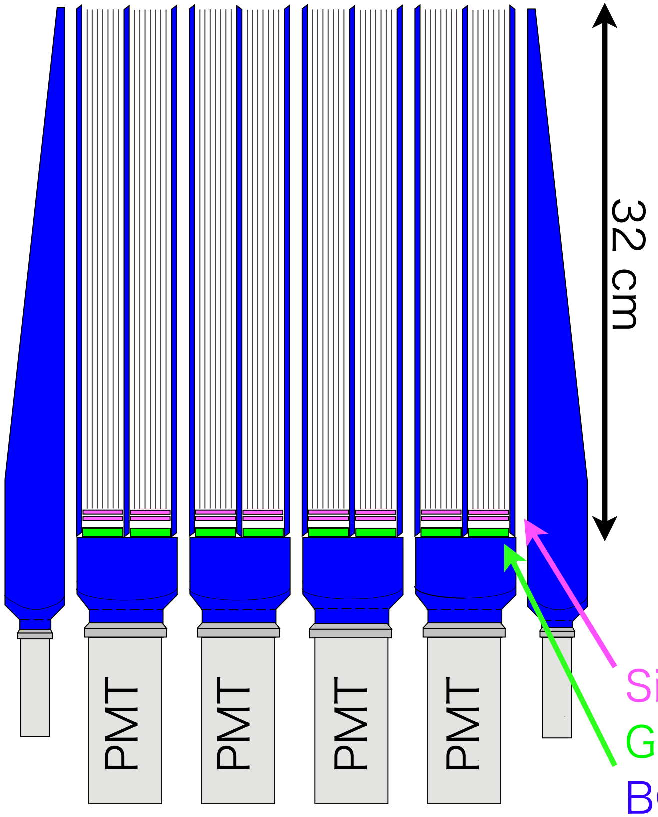
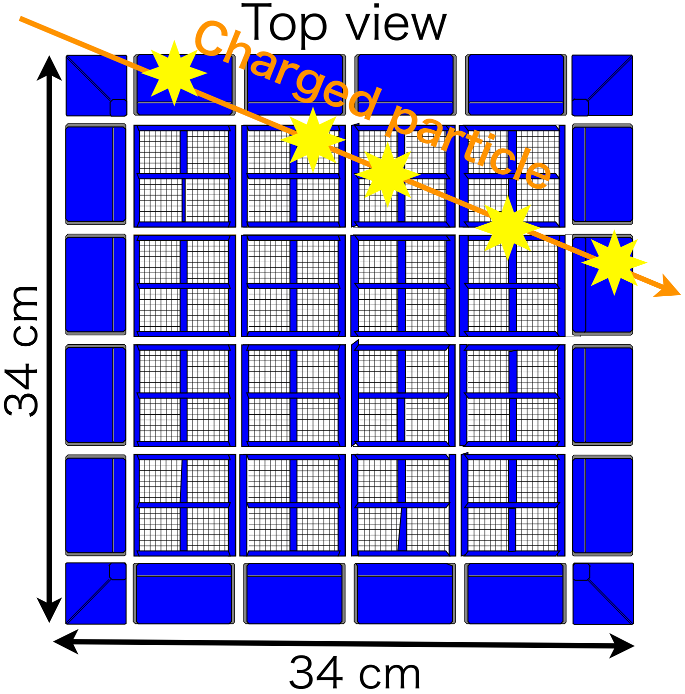
Hard X-ray detector onboard Suzaku (朱雀)

Cross-section view

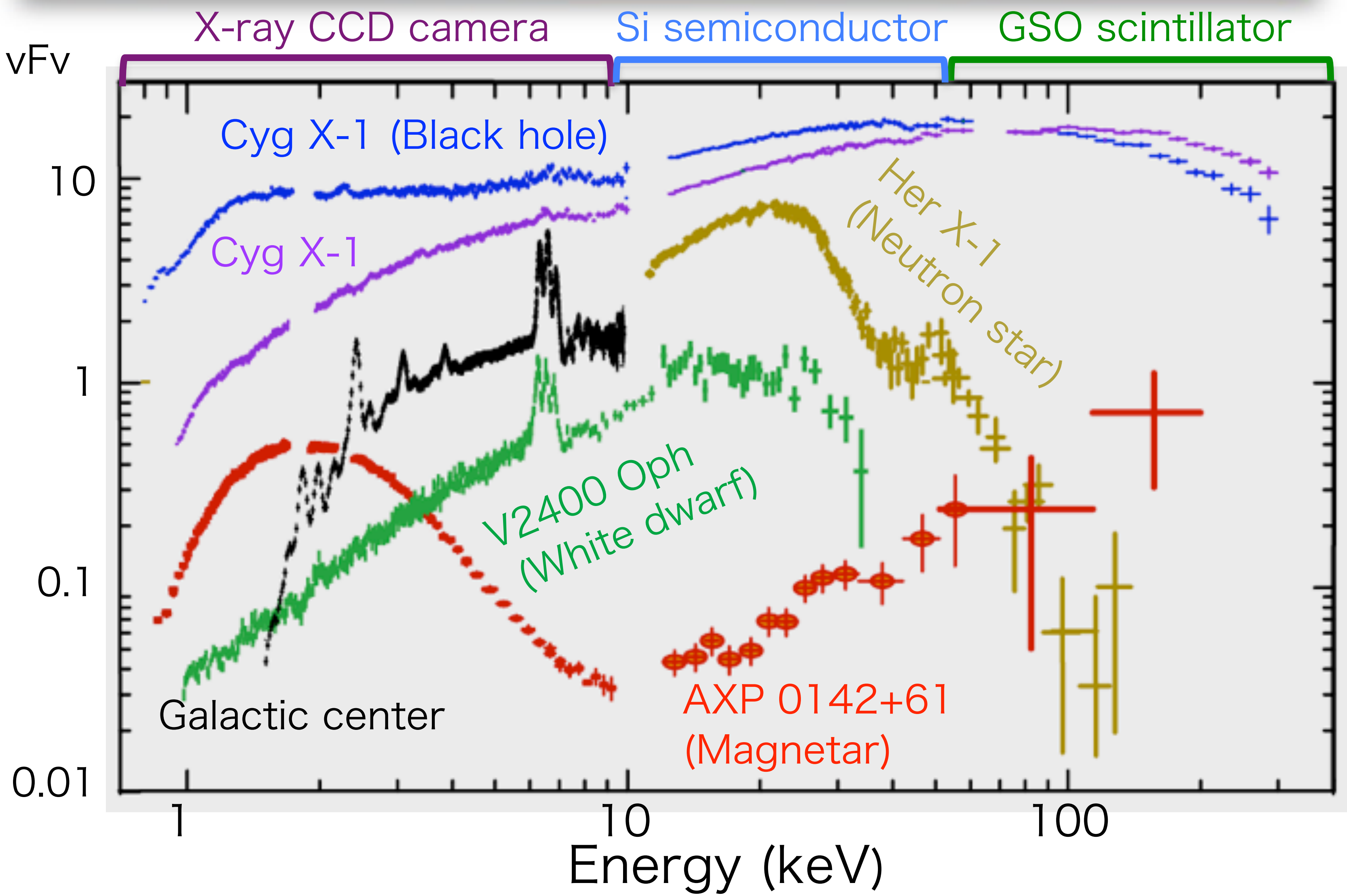


Top view



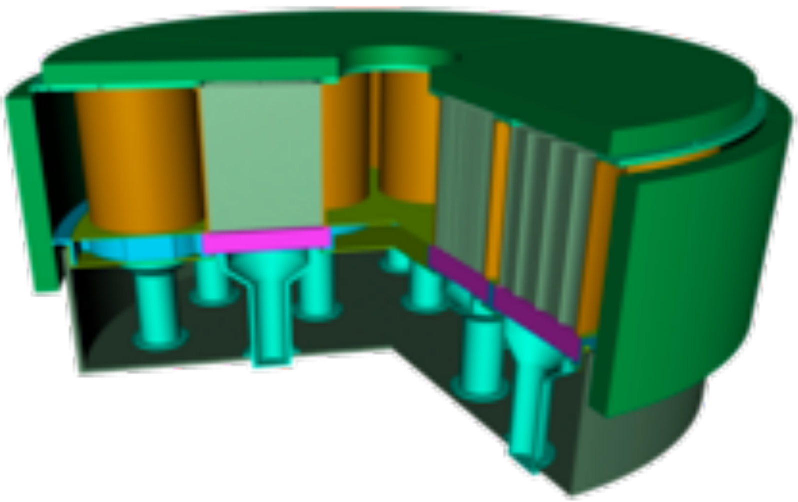
Scintillation counters are used as X/γ-ray detectors as well as anti-coincidence shields

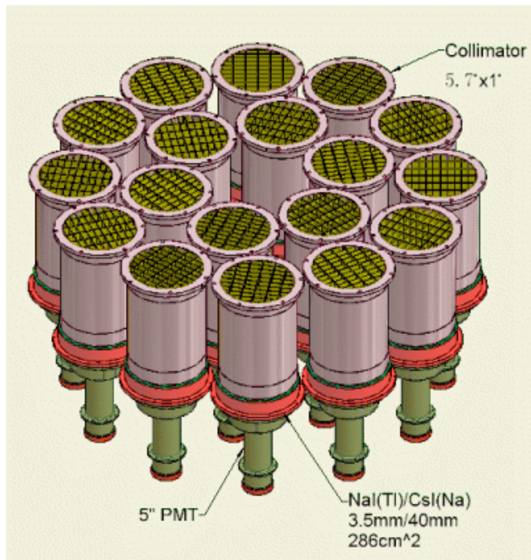
4-3. Examples of Suzaku Spectra



4-3. Chinese X-ray Satellite

- Hard X-ray modulation telescope (HMXT)
  - Planned X-ray space observatory from China
  - Scheduled to be launched b/w 2014 and 2016
  - Developed by MOST, CAS, and Tsinghua University
  - 18 NaI(Tl) scintillators as photon absorbers
    - Large area (286 cm^2)
    - 20-200 keV energy range
  - CsI(Na) scintillators as anti-coincidence shields





5. Review

- Scintillator is widely used to detect radiation.
  - Scintillation light is produced by ionizing events.
  - Scintillation detector is obtained when scintillator is coupled to electronic light sensor such as phototube or photodiode.
- Scintillator has been utilized to detect cosmic X/γ-rays as well as to reduce cosmic radiation background with anti-coincidence technique.